On high-speed turning of a third-generation gamma titanium aluminide

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Abstract

Gamma titanium aluminides are heat resistant intermetallic alloys predestined to be employed in components suffering from high mechanical stresses and thermal loads. These materials are regarded as difficult to cut, so this makes process adaptation essential in order to obtain high quality and defect-free surfaces suitable for aerospace and automotive parts. In this paper an innovative approach for longitudinal external high speed turning of a third generation Ti-Al_{45}-Nb_8-$C_{0.2}$-B gamma titanium aluminide is presented. The experimental campaign has been executed with different process parameters, tool geometries and lubrication conditions. Results are discussed in terms of surface roughness/integrity, chip morphology, cutting forces and tool wear. Experimental evidence showed that, due to the high cutting speed, the high temperatures reached in the shear zone improve chip formation, so crack-free surface can be obtained. Furthermore, the use of a cryogenic lubrication system has been identified in order to reduce the huge tool wear, which represents the main drawback when machining gamma titanium aluminides under the chosen process conditions.

Keywords: high speed turning, third generation gamma titanium aluminide, surface integrity, lubricoolant strategy

1. Introduction

The development of advanced lightweight structural materials is a key point for automotive and aerospace applications, in order to improve engine performances and efficiency, and to satisfy the always more restrictive environmental regulations aimed at reaching a decisive decrease of CO_2 emissions responsible for the green house effect. In this context gamma titanium aluminides, due to a favourable combination of mechanical and thermal properties, have been identified as predestined candidates to substitute Nickel-based materials [1-3]. In general terms, γ-TiAl alloys presents a remarkable strength to weight ratio, being their density approximately half that of Nickel-based superalloys, together with high stiffness, high elastic modulus and strength retention at elevated temperatures, high refractoriness and oxidation/ignition resistance and good creep properties.

Promising fields of application have been identified both in rotating and non-rotating parts, as low pressure turbines, compressor vanes, swirl nozzles, automotive engine valves and turbocharger wheels [4-6]. The relatively low density of the material leads to reduced engine weights, resulting in higher thrust to weight ratios, while its higher operating temperatures at the pressures acting upon them allow to improve the engine efficiency. The reduced inertia is also an advantage for rotating parts. The adaptation of smaller components, and hence smaller sized engines consequently limits fuel consumption. Such alloys have advantages versus Nickel-based alloys in the intermediate temperature interval of 650-800°C while, in comparison to titanium-based alloys like Ti-Al_6-V_4, gamma titanium alloys could be employed at decisive higher temperatures. Therefore, in aircraft engines, this material is destined to substitute Nickel-based alloys in the hot parts of aircraft engines, while the usage of conventional titanium alloys is limited to the cold part in front of the combustion chamber.

Up to now, a wide-ranging usage of this materials in serial applications is limited, despite of the attractive mechanical and thermal properties. This can be traced back to high material and processing costs, especially due to its poor machinability. In fact gamma titanium aluminides are regarded as difficult-to-cut alloys, because of their low ductility combined with high hardness and brittleness at room temperature, low thermal conductivity and high elevated temperature strength, low fracture toughness and chemical reactivity with many tool materials [7]. One of the main problems related to the poor machinability of these materials is the formation of defects in the form of micro-cracks and micro-fractures on the workpiece surface [7, 8]. These defects act as initial point for crack propagation resulting in part failure, which is completely unacceptable for safety-critical components, whereas surface integrity is indispensable.

Machining investigations with defined cutting edges published in literature highlight that under conventional process conditions (at relatively low cutting speed) it is impossible to obtain crack-free surfaces, and that the sub-surface microstructural damages consist also of material pullout, surface drag with deformed lamellae, cracked TiB_2 particles and hardened layers [9, 10]. One opportunity to avoid the arise of cracks was identified in grinding [11, 12] and in high speed milling with ball end tools. In particular, results presented by Mantle and Aspinwall [13] have shown that samples without cracks and with average surface roughness less than R_a = 1.5 μm could be obtained, although microstructural alterations were detected. These studies [9-13], executed on a cast and treated Ti-Al_{45}-Mn_2-Nb_2+0.8 vol.% TiB_2 XD alloy, evidence a strong correlation between process parameters and workpiece surface integrity, and suggest that high speed cutting strategies result in better surface conditions.

The interest in machinability of gamma titanium aluminides is still increasing, focussing on milling [14, 15], drilling [16] and turning [17-19] processes. However, further work is needed to optimize machining strategies leading to high productivity at aerospace quality levels, where surface integrity is indispensable for the in-use component, focusing on tool and process design as well as the development of adapted high performance lubricoolant strategies. With respect to this last aspect the potential benefits of cryogenic lubrication, which have proven to be effective in machining of other Titanium alloys, have not been investigated yet.

The potential of adapted cutting inserts in combination with a cryogenic lubricoolant strategy is given in the presented results. More in detail, in the conducted experimental tests it was aimed to generate high temperature in the shear zone to soften the material. Hence, the ductility is increased and therefore chip formation is improved resulting in enhanced workpiece surface quality. Longitudinal external turning operations have been conducted on a gamma titanium aluminide, with varying of process parameters, tool geometries and lubrication conditions.

2. Experimental approach

In longitudinal external turning investigations the machinability of the gamma Titanium-aluminide alloy Ti-Al_{45}-Nb_8-$C_{0.2}$ TNB-V3 was investigated. This material belongs to third generation of high performances gamma titanium aluminides, as well as Ti-Al_{46}-Nb_8-B_1 (proportions in atomic percentage), which have been developed in the past few years. From the chemical composition standpoint, the main difference with the predecessors is related to the increased content of Niobium: this allows higher strength values and enhanced thermal stability. It has also been shown that a 5-10 at.% addition of Nb significantly improves oxidation behaviour and increases creep resistance [20]. Microstructure of the workpiece material is shown in Figure 1.

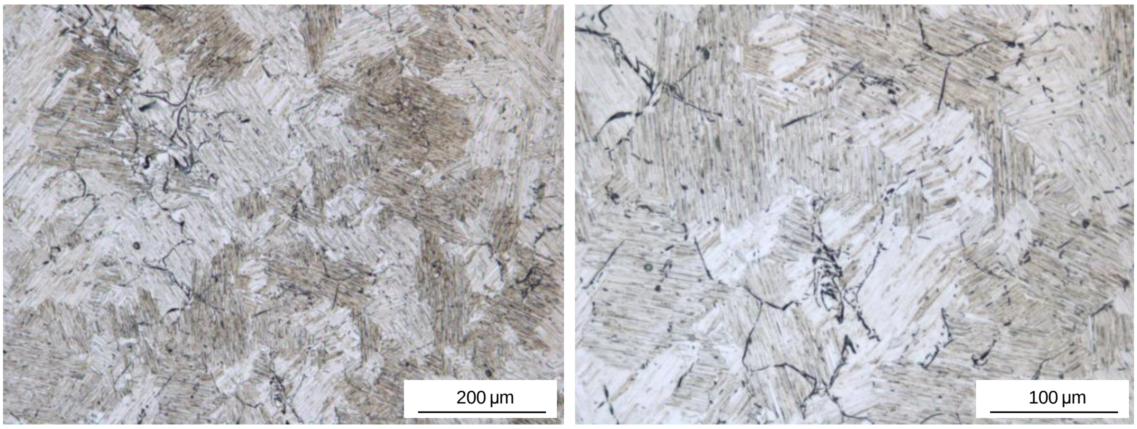


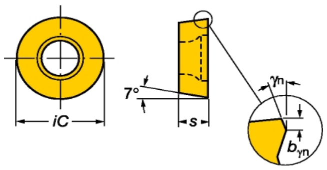
Figure 1: Optical micrograph showing microstructure of workpiece Ti-Al_{45}-Nb_8-$C_{0.2}$-B alloy, at 100X (left) and 200X (right) magnification

For the experimental machining trials uncoated tungsten carbide ISO K10/K20 inserts have been applied. The tool geometries and cutting angles are described in Figure 2. More in detail, round RCMX 120400 inserts have been used under a minimum quantity lubrication (MQL) system, for cutting conditions ranging as follows: cutting speed v_c from 60 to 100 m/min, feed f from 0.05 to 0.2 mm and depth of cut a_p from 0.1 to 0.4 mm. Furthermore, at fixed process parameters (v_c = 100 m/min, f = 0.1 mm and a_p = 0.4 mm) negative geometry CNMA 120408 inserts with different chamfer dimensions (Figure 2) have been applied under both dry and cryogenic lubrication conditions (Figure 3). The turning experiments were performed on an Index GNU 800 lathe. For the evaluation of the machinability, chip morphology, tool wear and corresponding surface roughness, surface integrity and cutting forces were considered.

Cutting material: ISO K10/20

Tool geometry: **RCMX 12 04 00**
$\gamma_0 = 0°$, $\alpha_0 = 7°$, $\lambda_0 = 0°$, $r_\beta = 8$ µm

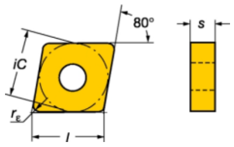
Chamfer: $\gamma_n = 15°$, $b_{\gamma n} = 0.20$ mm



Cutting material: ISO K10/20

Tool geometry: **CNMA 12 04 08**
$K_r = 95°$, $\alpha_0 = 6°$, $\lambda_s = -6°$

Chamfer:



Sharp tool	$\gamma_n = 20°$, $b_{\gamma n} = 0.25$ mm	$\gamma_n = 20°$, $b_{\gamma n} = 0.50$ mm

Figure 2: Cutting inserts specifications

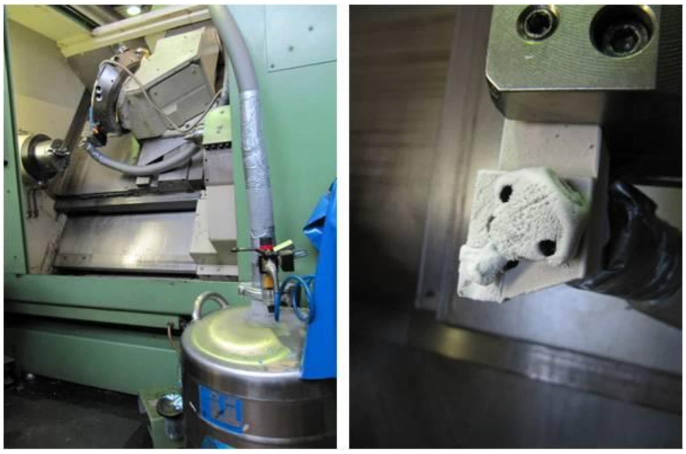


Figure 3: Experimental set-up with cryogenic lubrication equipment.
The detail shows a CNMA insert at the end of a cutting test

3. Results and discussion

Objective of the experimental results obtained in longitudinal turning operations was to describe the correlation between tool geometry, cutting conditions and lubricoolant strategy, and the effect on surface quality. Furthermore, chip shape, cutting forces and tool wear were investigated.

3.1 Chip morphology

The high level of brittleness of gamma titanium aluminides retained up to high temperatures and the poor material behaviour to deform plastically complicate the machining decisively, mainly due to the formation of discontinuous and segmented chips [21]. Therefore, the machined workpiece material is ripped out of the machined surface resulting in surface defects such as fracture structures and extensive cracks [9]. The chip cross-section in Figure 4 illustrates the longitudinal section of a typical saw-tooth chip showing the angular, needle-shaped chip lamellae obtained during a turning operation.

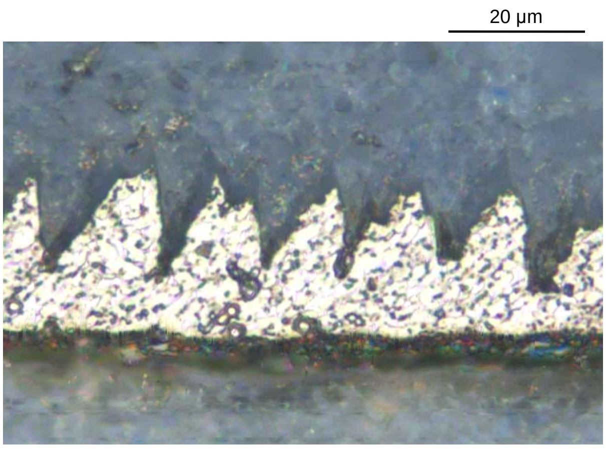


Figure 4: Longitudinal section of a typical saw-tooth chip obtained in turning tests
with RCMX cutting inserts, for MQL lubrication conditions

Figure 5 depicts the correlation between the chip shape/size and the cutting parameters for the tests executed with round and chamfered RCMX inserts, by adopting the MQL lubrication conditions. Under the chosen range of parameters, chip size raises with the increase of the depth of cut, especially with the transition from a_p = 0.3 mm to a_p = 0.4 mm, and with the increase of the cutting speed up to v_c = 100 m/min. Furthermore, an amplification of the chip size due to an increase of feed, within the range f = 0.05-0.2 mm, is slightly perceivable. The high temperatures achieved in the shear zone, as a consequence of the high deformation of the material, allow to soften the material and to improve the chip formation. In particular, the heat in the shear zone can be traced back directly to the cutting speed, and coiled chips are formed.

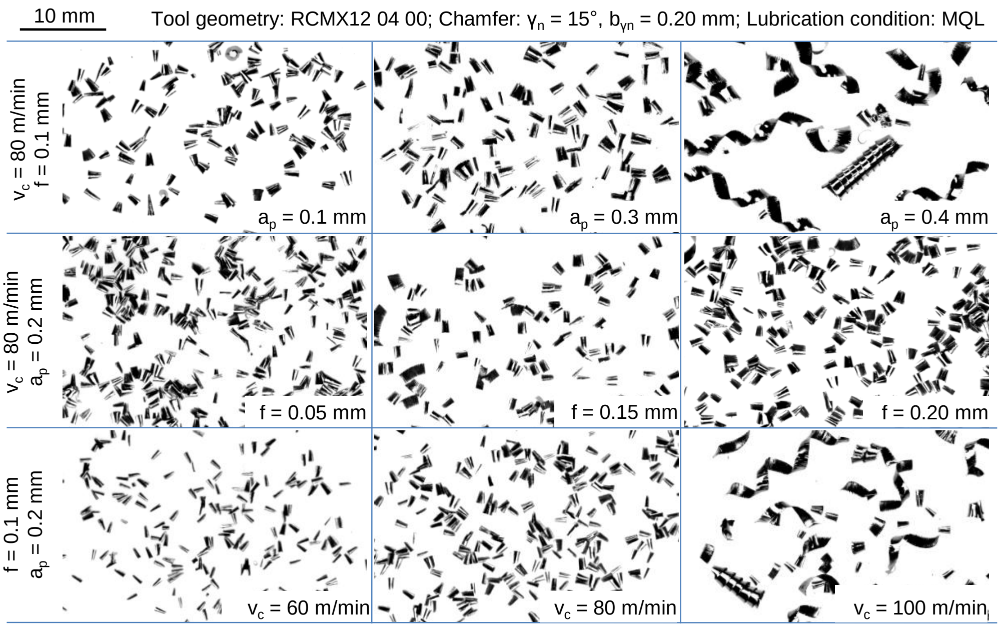


Figure 5: Chip morphology as a function of cutting parameters, for MQL lubrication conditions

On the other hand, at fixed process parameters (equal to v_c = 100 m/min, f = 0.1 mm and a_p = 0.4 mm) and with CNMA cutting inserts, chip dimension increases directly with stronger material deformation resultant to the different cutting tool geometries. More in detail, the use of chamfered tools, instead of sharp ones, allow to increase the average chip size and length, both with dry and cryogenic lubrication conditions, as shown in Figure 6. Furthermore, with the liquid nitrogen lubricoolant, the huge reduction of the temperatures in the tool/workpiece contact area reduces the size and fragments the chips, as expected. The higher temperatures reached in dry conditions are confirmed by the different colour of the chips, which are darker than those obtained with the cryogenic lubrication system.

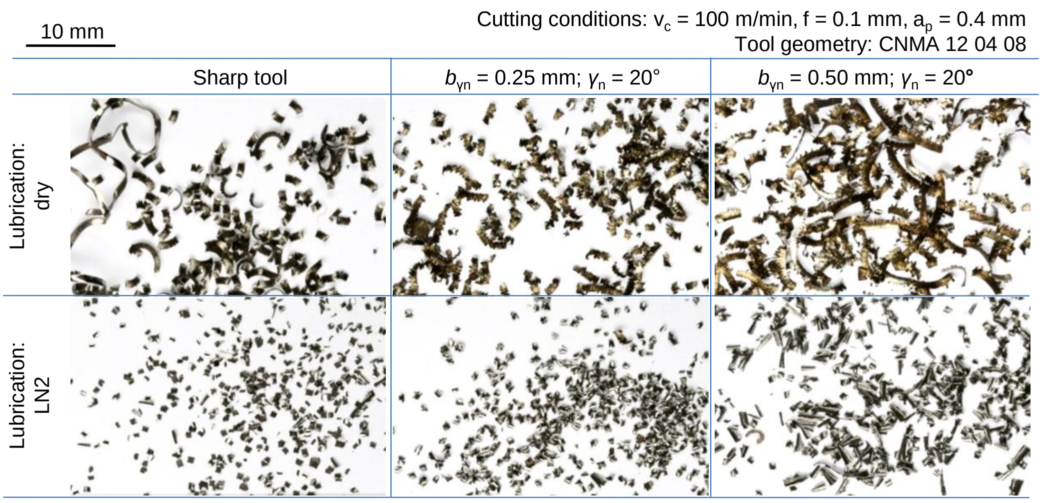


Figure 6: Chip morphology for dry and cryogenic lubrication conditions: comparisonbetween different CNMA tool geometries,at fixed process parameters

3.2 Surface quality

In Figure 7 some of the outcomes obtained in terms of arithmetic mean roughness R_a and maximum roughness profile height R_z are compared, considering different tool geometries, cutting parameters and lubrication conditions.

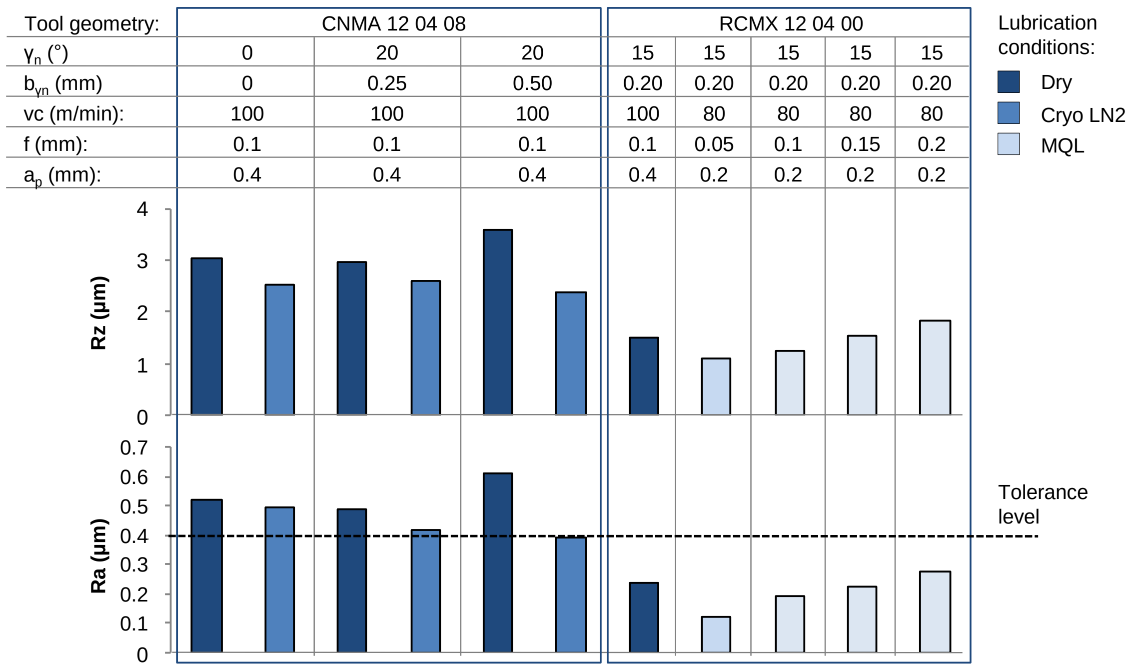
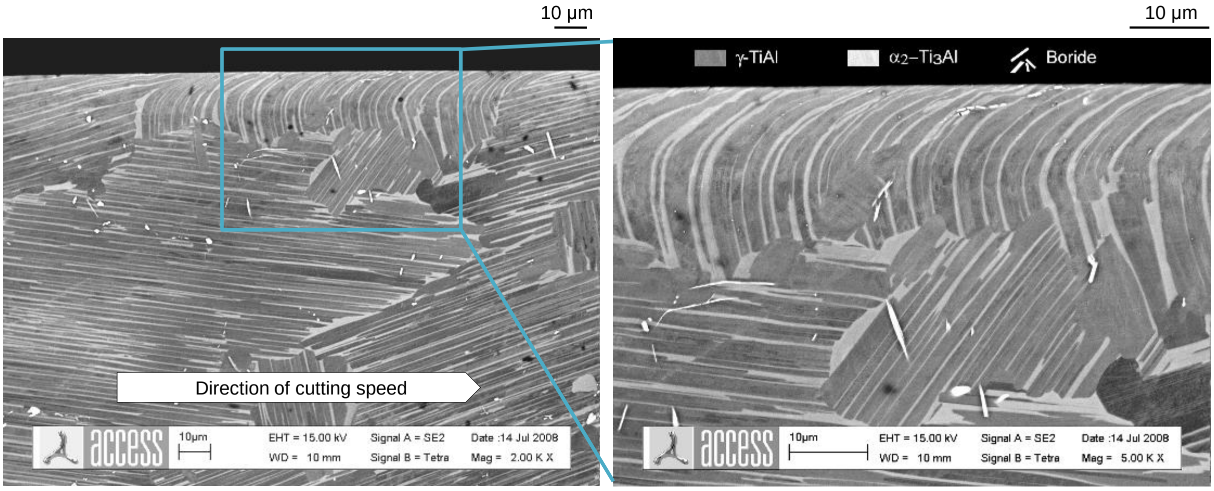


Figure 7: Roughness results

With an appropriate selection of the process variables it is possible to maintain the roughness indexes below the tolerance limit, equal to R_a = 0.4 µm, imposed by the rigorous demands of the aerospace sector [22]. By using the minimum quantity lubrication system, the results obtained with uncoated carbide round and chamfered RCMX inserts highlight that a high speed turning strategy could be successfully implemented. The effects of process parameters follow the literature: Figure 7 shows for instance, for the test executed at v_c = 80 m/min and a_p = 0.2 mm, the decrease of roughness indexes R_a and R_z, with an approximately linear trend, as a result of the reduction of the feed from f = 0.2 mm to 0.05 mm.

Accordingly to Section 3.1, a favourable chip formation was achieved, and this reflects directly on machinability. Some samples, characterized by satisfactory values of surface roughness, were sectioned and analyzed by SEM: high quality and crack-free surfaces can be produced, as shown in Figure 8. Sub-surface microstructural alterations were noticed and, in particular, the effects of surface drag can be evidenced by the lamellae deformation. As reported by Mantle and Aspinwall [13], this phenomenon indicates strain at high temperatures.



Cutting conditions: v_c = 80 m/min, f = 0.1 mm, a_p = 0.4 mm, MQL
Tool geometry: RCMX 12 04 00, γ_n = 15°, $b_{\gamma n}$ = 0.20 mm

Figure 8: Cross section of the machined surface, showing surface integrity with lamellae deformation in cutting direction

Tool geometry also plays a significant role: at fixed process parameters the results obtained in dry conditions with RCMX inserts (edge radius r_ε = 6 mm) are better than those acquired with CNMA tools (r_ε = 0.8 mm), although with cryogenic lubrication. However, for similar CNMA tool geometries, the use of liquid nitrogen is suitable to improve the surface finish by reducing tool wear.

In Figure 9, showing the roughness profiles and the machined surfaces from the beginning to the end of the tests, the deterioration of quality due to tool wear is easily perceivable in dry conditions. With a heavily worn tool (see also Figure 11 - Section 3.4), surface cracks with a characteristic dimension of the order of tens of micron appear and make the results unsatisfactory.

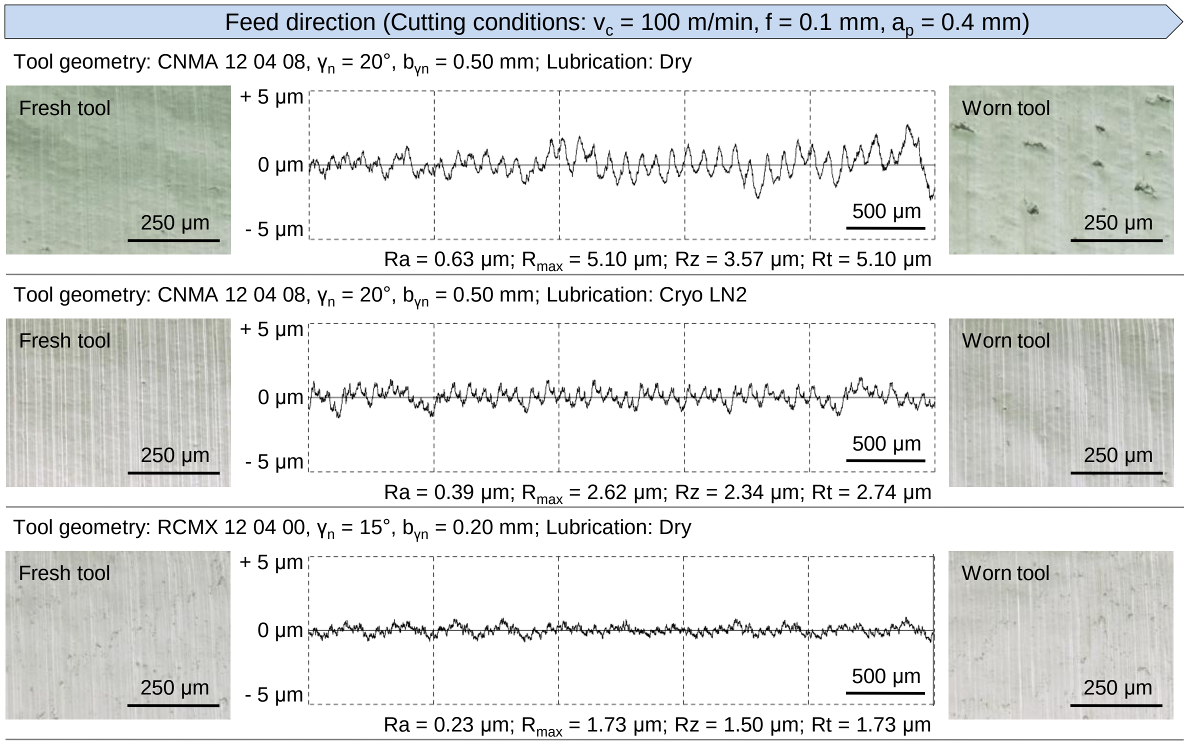


Figure 9: Machined surfaces with fresh/worn inserts and roughness profiles (type R), at fixed cutting parameters.

3.3 Cutting forces

The measured cutting forces for turning with RCMX tools are shown in Figure 10. The values of the three force components (passive force F_p, feed force F_v and cutting force F_c) refers to fresh cutting inserts, considering the measurements taken immediately after the tool-workpiece engagement.

For both round and chamfered tool geometries it is implied, that passive forces are always higher than the other components, whereas the influences of process parameters on the forces are clearly visible. The cutting speed v_c has the slightest impact on the cutting forces in comparison to the other considered variables, with a moderate increase of the measured values. Much more distinctive effects are due to the increase of feed and depth of cut, particularly on passive and cutting forces. The graphs suggest that a gain in material removal rate should be possible by increasing the chip cross section through variations of feed rather than of depth of cut.

Cutting forces increase rapidly as a result of tool wear, and this observation can already be pointed out in the first seconds of machining time and for all the executed tests. Adopting the strict process parameters chosen for the experimental plan, this phenomenon is particularly evident in absence of lubricoolant supply (Figure 11). Furthermore, the cutting forces are influenced by the tool geometry. A comparison between CNMA inserts with varied geometries highlight that passive and cutting force measured with sharp tool are lower than those measured with chamfered tools.

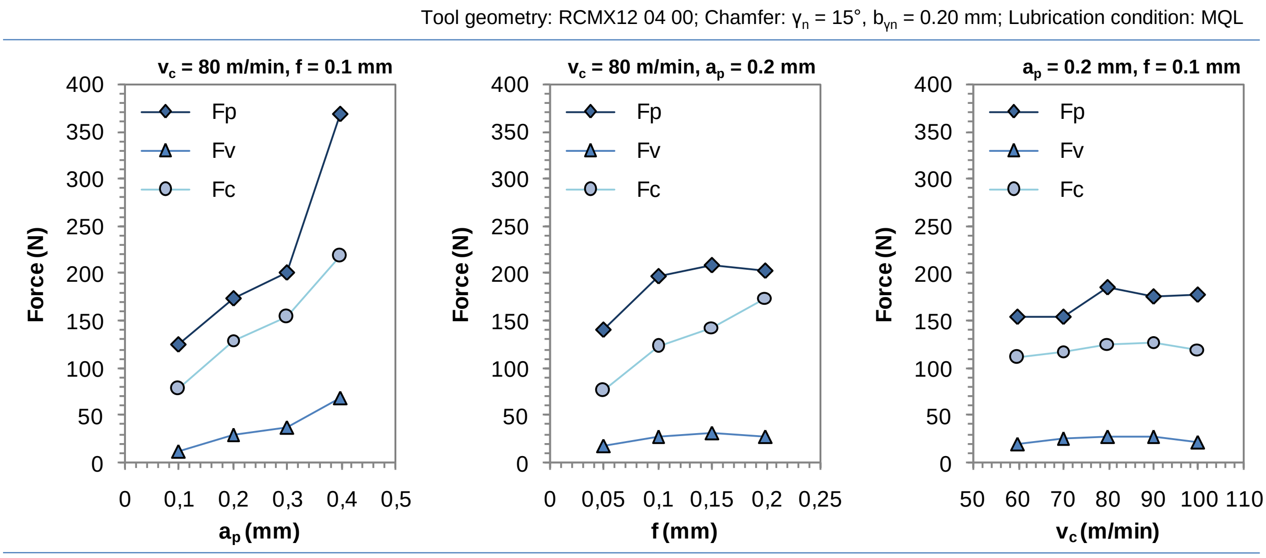


Figure 10: Cutting forces results (F_c = cutting force, F_v = feed force and F_p = passive force) withRCMX round inserts and for MQL lubrication conditions.

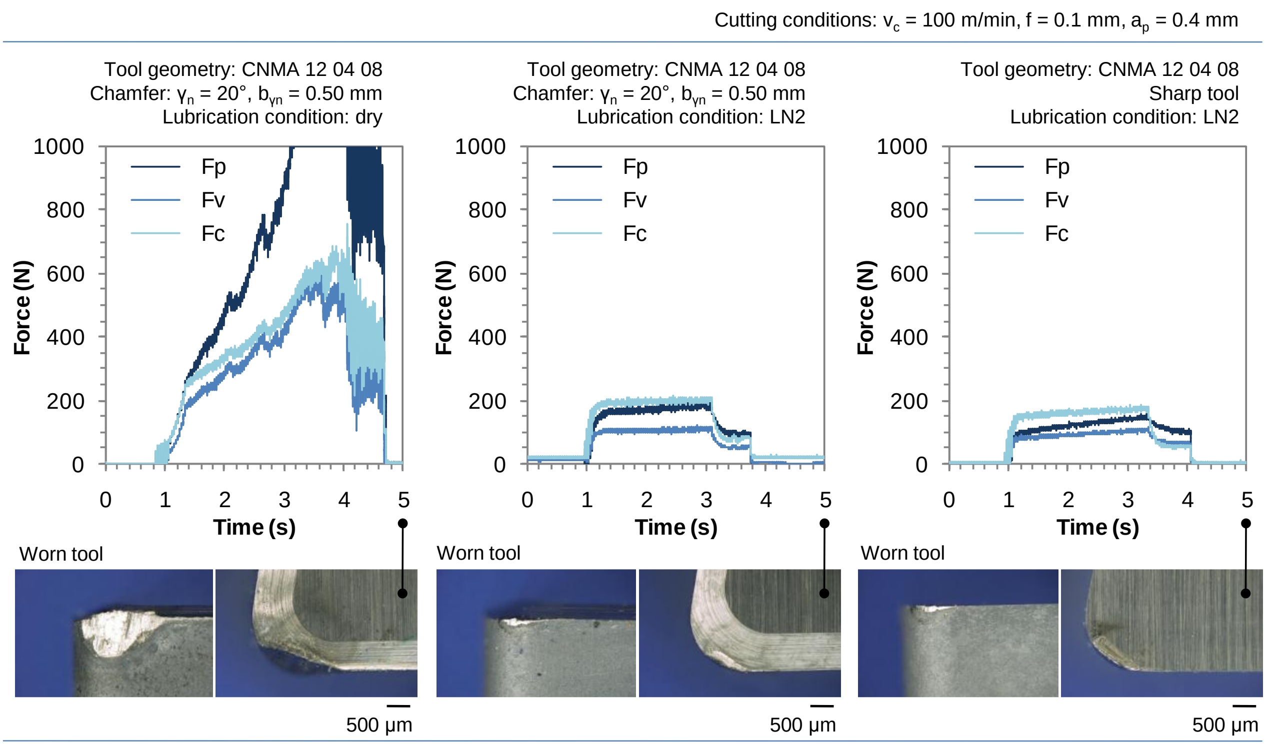


Figure 11: Cutting forces measurements and tool wear with CNMA inserts, referring to dry and cryogenic lubrication conditions.

3.4 Tool wear

The previous considerations evidence that the alloy's machinability improvement is related to the temperatures reached in the shear zone, that allow to overstep the brittle/ductile transition and to soften the material in order to obtain high quality and crack free surfaces. Therefore, the heat can be considered itself as a tool. Conversely, the main drawback regarding this machining strategy is that the increased thermal impact to the cutting edges of the tools result in stronger tool wear, as shown in Figure 11 and in Figure 12 for CNMA and RCMX inserts, respectively. In addition, the discontinuous formation of lamellar chips, which involves a constant shift between compression and sliding phenomena in the shear zone, subjects the tool to a mechanical and thermal alternate load [21].

Figure 12: Tool wearfor RCMX inserts and minimum quantity lubrication

Tool life with uncoated carbide inserts is extremely short and cutting operations with worn tools results in poor surface quality, especially the presence of micro-cracks, surface hardening and residual stresses. The results (Figure 11) show, that cryogenic lubrication could be successfully applied to reduce the thermal load on the cutting edges at high process parameters, providing potentially enormous benefits.

4. Conclusion and outlooks

Poor machinability of gamma titanium aluminides and furthermore the high manufacturing costs limit the wide spread of those material in the market, although some production processes has already been qualified for aerospace engine components, in which surface integrity is of major importance.

As this presented results have shown, the machining of the Ti-Al_{45}-Nb_8-$C_{0.2}$ intermetallic γ-TiAl alloy can be enhanced significantly, as far as the surface quality is concerned, by an adjustment of process parameters and of cutting edge geometry. In particular, with cutting speed up to v_c = 100 m/min, the brittleness of this material drops off, due to high temperatures reached in the shear zone and chip formation is improved. Adopting the minimum quantity lubrication, in longitudinal external turning tests with round, chamfered and uncoated RCMX inserts it was possible to obtain smooth (R_a< 0.4 µm) and crack-free surfaces, even if transverse cross-sections of the machined samples highlighted deformation of the lamellae. The tests performed with CNMA inserts show roughness results slightly superior to the tolerance limit imposed by aerospace industry: consequently small ratios of depth of cut a_p to the corner radius r_ε should be suggested in turning operations.

The described and adopted strategy to high speed machine the material increases on the one hand side the machinability, but results on the other hand in a high thermal load of the cutting edge. The poor tool life is still the main disadvantage to be optimized. A promising opportunity which yielded interesting results is the use of cryogenic lubrication with liquid nitrogen.

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